BNL-35173

PHYSICS RESEARCH OPPORTUNITIES WITH SYNCHROTRON X-RADIATION

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BNL--35173

DE84 016987

ABSTRACT

New X-ray sources of substantially increased brilliance would be available from undulator magnets operating on a new-generation 6 GeV storage ring. To understand what research opportunities would be provided by such improved sources, a number of existing x-ray scattering techniques are briefly described with a qualitative analysis of their requirements for source brilliance. In addition to improvements of existing techniques which will permit application to a generally broader range of problems, new opportunities for magnetic and inelastic x-ray scattering are discussed.

May 1984

A revolution in x-ray research has resulted from the availability of synchrotron radiation from storage ring bending magnets and recently from wiggler magnets.[1-3] Another extraordinary improvement in source brilliance is anticipated when undulator magnets begin to produce coherent x-ray beams on the next generation of higher energy (6 GeV) storage rings.[4] These new devices will provide many new opportunities for x-ray research not possible with current sources.

There are two basic classes of synchrotron x-ray experiments — scattering and spectroscopy. Both of these techniques will be considerably improved by the next generation of sources of increased brilliance. In this paper, the emphasis will be on the research frontiers and particularly the impact of brilliance.

The history of x-ray source brilliance, with is defined as the number of photons per second per unit source area per unit source divergence per 0.1% bandwidth, is shown in Figure 1. The brilliance of a conventional x-ray tube is on the order of 10^7 photons/sec x mm^2 x $mrad^2$ x 0.1%BW. The introduction of rotating anodes increased brilliances in the early sixties by an order of magnitude. The introduction of synchrotron sources produced the first qualitative improvement in brilliance over the x-ray tube; effective brilliance was increased by some four to six orders of magnitude. Although there is an enormous difference (about two orders of magnitude) between using a bending magnet during parasitic beam time at the Stanford Synchrotron Radiation Laboratory, and using the 54-pole wiggler[3] during dedicated operation, these are quantitative increases when viewed in this historical perspective. The brilliance potentially available from an undulator on a 6 GeV ring represents a further increase of five to six orders of magnitude, and it will drive the next generation of synchrotron x-ray science.

Figure 2 describes the properties of synchrotron radiation. It shows the fundamental relationships between the critical wavelength produced by a bending magnet which provides a continuous spectrum as a function of wavelength and energy, and the undulator on which the new generation of experiments will be based. The undulator produces a peaked spectrum in which the photon wavelength, λ_p^m, depends on the harmonic number m, the magnetic period of the device λ_u, the electron energy γ (in units of mc^2), and a factor which includes the K parameter of the undulator device. This parameter is simply the magnetic field strength times its period, that is $K = 0.93\ B(T)\lambda_u(cm)$. One can tune an undulator over a small (say 10%) range by varying the magnetic field by changing the gap between the permanent magnet poles. A better way to tune it would be changing the magnetic period, but the technical aspects associated with this technique have not yet been studied in any detail.

The performance of an x-ray undulator on a 6 GeV machine running at some 100 milli-amps is shown in Figure 3. At a photon wavelength of 1Å this device would produce an approximately isotropic cone of radiation, emitting into a solid angle $(\Delta\theta)^2$ given by two times the photon wavelength over the length of the undulator. For a device 2 meters in length, $\Delta\theta \approx 10^{-5}$ radians. All the radiation of the fundamental wavelength would be transmitted by a pinhole 10 microradians in angular size; at 20 meters from the source this aperture would be 200 microns in diameter. The flux at the fundamental wavelength would be approximately 10^{15} photons/sec x 0.1% BW, and the brilliance about 10^{19} photons/sec x mm^2 x $mrad^2$ x 0.1%BW.

Having described the characteristics of undulator radiation, it is appropriate to provide a general overview of the new research opportunities before discussing specific examples. Figure 4 shows a general space-time plane which can be used to locate various physical phenomena. The ordinate denotes momentum transfer (in inverse angstroms) going to successively smaller resolutions, and distance (in millimeters) going to successively smaller length scales. The abscissa denotes energy, in volts, going to successively smaller energy scales and time, in picoseconds, going to successively smaller time scales. Currently, experiments with x-rays are generally done outside the central region. That is, they are done with energy-transfer resolution of less than 1 eV. They are done with momentum-transfer resolution generally poorer than 10^{-3} inverse angstroms. They are done with real-space resolution generally poorer than 10 microns, and they are done with time resolution generally longer than about a nanosecond. These are not hard boundaries. There are experiments which penetrate in various ways, but they are exceptions. The x-ray undulator, however, will permit us to work routinely in the central region. It is also very exciting to note that there will be possible overlaps. It will be possible to do both diffraction and microscopy simultaneously. It will be possible to do inelastic scattering and time-resolved scattering.

The principal techniques using synchrotron radiation in the x-ray region are based either on spectroscopic or diffraction techniques. Absorption spectroscopy[5], of course, is the technique that grew along with the development of synchrotron radiation. It grew increasingly more sophisticated as synchrotron sources grew more sophisticated, and it is an example which demonstrates very nicely how increases in flux and in brilliance have impact on the quality of science that is possible. Today, absorption spectroscopy experiments are routine and they have been used in many different areas. The following papers on materials science and biological applications will describe some of the most interesting applications. The present discussion is concentrated entirely on scattering: elastic scattering and inelastic scattering. Research based on these techniques constitutes the strongest case for the high-brilliance devices which will be available on the next generation of high-energy (6 GeV) storage rings.

Elastic scattering experiments are extraordinarily well-matched to synchrotron sources primarily because the natural opening angle of the radiation is on the order of a Darwin width of a perfect crystal. Thus, a momentum-transfer resolution on the order of 10^{-3} to 10^{-4} inverse angstroms is naturally achieved. Conventionally, such scattering instruments[6] have an energy resolution on the order of 1 eV. The energy resolution is not particularly important in an elastic scattering experiment except to reject Compton and fluorescent background. Later in this paper possibilities will be discussed for inelastic scattering experiments which will improve the energy resolution in order to access the region of thermal excitations in condensed matter.

Concentrating on elastic scattering experiments, there are a variety of different types of techniques: high Q-resolution, time-resolved diffraction, small angle scattering, anomalous scattering, standing wave diffraction, white-beam techniques, and grazing incidence scattering. Examples of each of these techniques will be described below to show in general what experimental work is being pursued and how these techniques would each individually benefit from the brilliance of the new generation of sources. Note also that there are new opportunities and new techniques such as magnetic x-ray scattering which will be impossible without the flux and brilliance of new sources. Similarly, diffraction microscopy would represent an important opportunity available with the new sources.

Before discussing the specific techniques, let me review the important general elements of brilliance. As described above, brilliance is the number of photons per sec per unit solid angle and unit area of the source. Scattering experiments require flux, collimation, and small beam size in varying degrees. Flux is necessary for studying lower-Z materials, for studying samples with few scattering particles (such as atomic microclusters), and for performing time-resolved experiments. Collimation is necessary in scattering experiments to study long-range coherence. In some cases collimation in only one angular direction is adequate, and the broad fan of highly collimated radiation from bending magnets and wigglers is utilized. But in other cases, such as in small-angle scattering and in some applications in wide-angle scattering (e.g., glancing angle scattering and transmission experiments in two-dimensional systems) it is exceedingly important to have a beam collimated in both spatial dimensions. Finally, the requirements for beam size: for studying small crystals; for restricted access as in a high-pressure experiment in a diamond-anvil cell; for investigating atomic clusters in narrow beams;and for diffraction microscopy. All of these applications involve sample dimensions on the 10- to 100-micron size scale. To summarize the impact of brilliance, if a technique or experiment has a requirement in each one of these categories - flux, collimation, beam size — it benefits directly from a high brilliance source. It is possible with an optical element, to trade collimation for beam size, but one can only improve both with sources of increased brilliance.

Now let me turn to specific examples. Figure 5 shows a diamond-anvil cell used in high-pressure diffraction experiments.[7] In order to access the crystal, which is typically on the order of 10-100 microns in size, one needs to get the radiation in and out through a relatively narrow angle defined by the gaskets. The diffraction experiment requires high collimation. Therefore, source brilliance will be the determining factor. Continuing on the theme of high pressure, it is important to mention that undulators proposed for a 6 GeV ring would produce fundamental radiation up to 20-kilovolt energy range. Such high-energy photons are one of the important advantages of these proposed high-energy machines. High-pressure experiments demand high-energy photons for penetrating the diamond cell. The signal measured in an experiment is a combination of the intensity, the transmission, and the reflecting power. Calculations[7] show that maximum signals are achieved at about 15 keV (λ = 0.8 Å).

The standing wave method[8] is another technique demanding brilliance. In these experiments a highly collimated x-ray beam is Bragg-reflected from the surface, as shown in Figure 6. During the process of dynamical reflection, a standing wave field penetrates the surface and atoms on or in the surface layers are excited into fluorescence. This signal depends on the atoms' location relative to the standing wave field, allowing the determination of the atommic positions. This technique requires a highly collimated incident beam to precisely define the incident angle. Furthermore, to look at a reasonably small area on the surface, a beam with relatively small size is necessary. Therefore, this technique benefits directly from brilliance. The best example of this research so far is the study of bromine on the surface of silicon. Figure 6 shows a scan of the crystal through its Darwin curve and the fluorescence from bromine. The location of the fluorescence peak relative to the rocking curve determines the position of the Br atom above the surface.

Grazing-incidence scattering[9-11] is another technique for getting information on the surface structure of materials, as shown in Figure 7. This method has been developed over the last few years, and it is a good example of the importance of brilliance. Grazing incidence scattering requires very high collimation in both the vertical and horizontal directions. High collimation is necessary in the diffraction plane in order to get high-resolution diffraction information. But high collimation is also necessary in the grazing-incidence direction in order to define the angle-of-incidence with adequate precision, since the angle-of-incidence is directly related to the penetration depth. Therefore, collimation in both spatial directions is extremely important. Again, small beam sizes are required because at glancing angles the sample does not have a large effective area. The requirements for both vertical and horizontal resolution, for small beam size, and for large flux (e.g., if it is a low-Z material) are precisely the requirements for brilliance. Using these grazing-incidence techniques, a variety of experiments have been done. One example is the study[10] of the commensurate-incommensurate transition of monolayers of lead on copper as shown in Figure 8. A study of the reconstruction of Germanium (100) has also been undertaken.[11] In favorable cases, for example Au(110),[12] rotating anode fluxes are adequate to do glancing-angle experiments, with signals of 10 counts a second. But for Si(111) 7x7, the signals are 10^4 weaker and it is impossible to use a laboratory source. The first Si(111) 7x7 reconstruction peaks were recently observed at SSRL.[13] We see an increasing number of surface structural problems where good x-ray structural information is already available or should be shortly. Ultimately, synchrotron x-ray techniques will permit the determination of the structures of surfaces with a degree of certainty that has been available for standard three-dimensional crystallography for some time.

The next example chosen is a variant of the glancing-angle technique using a liquid sample, as shown in Figure 9. This is very difficult diffraction geometry since the liquid surface must be kept horizontal. Note that this experiment is also very demanding in collimation as well as flux. Using surface [illegible]ection scans, such as shown in the Figure, direct measureme[illegible] [illegible]een made of the surface-induced smectic A phase above the nemati[illegible] [illegible]ic A phase transition in liquid crystals.[14]

Surface d[illegible] [15-17] studies can often be done to advantage in a transmission ge[illegible] [illegible]hich also requires two-dimensional collimation. If the incident wave-vector is very well defined in its divergence in the diffraction plane one can measure long coherence lengths. However, if this radiation comes from a bending magnet or a wiggler, it will have a large divergence perpendicular to the plane, which will mean that the resolution function is elongated. Two-dimensional scattering is a rod in reciprocal space, as shown in the inset to Fig. 10, and it is oriented perpendicular to the resolution function in the transmission geometry. The anisotropy of the resolution function is such that failure to match the resolution with the scattering profile reduces the signal by up to a factor of 100. With an x-ray undulator, which would provide a very highly collimated beam in both spatial directions, one would have an isotropic resolution function. As a result, transmission-geometry experiments, which are favorable for many cases, could be performed without paying this large price in signal.

Figure 10 shows some results from an experiment[15] that was done without the advantages of resolution focusing. This experiment demonstrates the lack of long-range order in two-dimensional crystal systems confirming theoretical predictions made decades ago, and helping to establish the basis for the study of 2D melting. Another approach to the study of 2D phase transitions involves graphite substrates. A whole family of measurements on phase transitions of various types has been made using exfoliated graphite samples.[16] Recently data from monolayers on single crystal graphite has been obtained[17], as shown for krypton in Figure 11. The signal rates are reasonably substantial, on the order of 1000 counts per second, using an 8-pole wiggler at SSRL. However, if one is considering a more ambitious experiment, considerably more flux is necessary. One experiment that is very interesting is the behavior of monolayer helium.[18] Scaling the krypton data shown in Figure 11, one would predict a count rate of 1 count/sec with existing sources. The improvement anticipated at the new facilities would be about an order of magnitude more flux, using an instrument which could provide wave vector resolution of about 10^{-4} Å^{-1}. Large bandwidth multilayer monochromators could be used to gain an additional factor of 100 in signal at the expense of resolution. This trade-off would be advantageous for studying the 2D crystal-to-superfluid transition.

Time-resolved diffraction studies are also in the category of flux-demanding experiments. Figure 12 displays some results from time-resolved experiments[19] done at Cornell in the last few years looking at the properties of silicon and germanium during laser annealing. In this experiment, the diffraction pattern is measured as a function of angle.

The x-ray beam is synchronized with the laser-annealing pulse to follow the behavior of the surface structure as a function of time after the initiating laser pulse. As shown in Figure 12 the Bragg peak is extended, showing the thermal heating of the surface. From these data it is possible to determine a precise thermal profile of the surface and follow in detail the process of recrystallization following the laser pulse. In this work, the time resolution was on the order of 5 nanoseconds.

There are interesting time-resolved experiments spanning a wide range of time scales, and an example of data taken on the scale of minutes is shown in Figure 13. This particular experiment involves small-angle scattering studies of phase separation in borate glass.[20] Although such experiments are possible on the time scale of minutes, one has a great deal more flexibility in choice of problem (that is, shorter time-scale) if more photon flux is available. Note also that small-angle scattering experiments are experiments which need two-dimensional collimation, so x-ray undulators are the ideal sources.

I would like to turn now to a discussion of prospects for new kinds of experiments which have not yet been undertaken on existing storage rings. One of these is magnetic scattering.[21] There is a relativistic term in the interaction of the x-rays with matter that couples the electromagnetic field of the photon to the magnetization of the solid. The scattering structure factor is down by two to three orders of magnitude and the cross-section for iron, for example, is down by about 10^6. Although these cross-sections are small, scattering should be easily measured with available fluxes from storage rings.

The opportunity exists to do experiments that are not in the traditional area for neutron research, for example very high Q-resolution magnetic scattering. Wave vector resolutions of 10^{-4} $Å^{-1}$ come naturally with a synchrotron x-ray scattering instrument. It turns out that there are terms in the magnetic cross-section which differentiate the spin and the orbit. There are anomalous magnetic-scattering effects. Unlike neutron scattering, small samples are perfectly adequate for x-ray experiments. One could study magnetic materials which have high neutron-absorption cross-sections and, most interestingly, it should be possible to study surfaces. Surface-enhanced magnetism is an interesting field and very little good data are available on the magnetic structure of surfaces. There should be magnetic analogues to the surface-reconstruction problems, and these could potentially be seen with the high-brilliance sources.

A second example of new techniques which demand brilliance is inelastic scattering, with energy resolution on the order of thermal (meV) energies. Inelastic scattering experiments have been done, although not to a great extent, with ~1 eV energy resolution.[22] Moving into the regime of a few millivolts[23] would greatly increase the range of study of physical phenomena of interest in condensed matter physics.[24] There would be a number of potential advantages of x-rays in the range of energy and momentum transfers where interesting cooperative phenomena take place. Of course, x-rays have the general advantage that they couple directly to the electronic charge. There are additional specific advantages in each of the three separate regions of energy and momentum transfer shown in Figure 14. In region I excitations in disordered materials can be studied without the kinematical restraints of neutron scattering. In area II, the energy transfer regime above 100 meV, x-rays techniques are ideal. A 15-keV photon can easily transfer energies in this regime, whereas the neutron flux available from reactor sources at these energies is very small. Finally, region III is the high momentum-transfer range, which is the work horse region for neutron scattering. Here x-rays would offer some complementary advantages to neutrons: small samples, neutron-absorbing materials, and perhaps the study of the dynamics of surfaces, for example.

Inelastic scattering depends, of course, on being able to get energy resolutions in the millivolt range. It is well known that using back-reflection techniques with perfect crystal monochromators one can achieve these kinds of energy resolutions. Figure 15 shows the energy resolution as a function of photon energy for various Bragg reflections in silicon. There are two curves which derive from two different types of structure factors for silicon reflections. Reflections with high Miller indices excited by photons in the 10-keV to 15-keV range will naturally provide energy resolutions below 10 meV. To implement techniques or instruments based on these ideas requires fairly elaborate engineering, particularly if the sources that will be used are not of high brilliance. One has to collect a large number of x-rays, both in the monochromatic beam and in the scattered beam. It is necesssary to bend the monochromator and analyzer crystals into a spherical shape. Bending introduces a strain which is hard to eliminate. Elaborate strain-relief schemes are being studied but the technology is difficult and such monochromators have not yet been achieved. Although we are optimistic that success will result, it has not yet been achieved. In the context of x-ray undulator sources, many advantages would be obtained for inelastic scattering with this highly collimated radiation. The technique is greatly simplified. It is not necessary to bend a crystal and no elaborate optical systems are required for focusing. Starting with a highly collimated source, one can use a flat pre-monochromator, a flat back-reflection monochromator, and another flat or cylindrically-bent back-reflection analyzer. With this instrument samples that are less than a couple of tenths of a millimeter will be adequate. Thus, it is clear that an x-ray undulator would be of great advantage for inelastic x-ray scattering.

Is millivolt resolution the limit for inelastic x-ray scattering? Probably for routine experiments that will be the limit, but other techniques are currently under discussion. One such method involves using nuclear-resonant scattering from Fe^{57} to monochromate x-rays to a level of 10^{-7} eV.[25] Using beams from the proposed 6 GeV x-ray undulator, one would have some 10^6 to 10^7 photons/sec. These levels are similar to beams from a standard x-ray tube, but with one part in 10^{11} monochromaticity. There are many interesting experiments which could be performed with this energy resolution, particularly in the dynamical properties of condensed matter and in iron-containing biological structures.

In conclusion it should be emphasized that it is not generally possible to predict the most exciting science that will be possible using improved sources of radiation. In this paper an attempt has been made to demonstrate the crucial importance of source brilliance in determining the limits of various current x-ray scattering methods. From this basis it is straightforward to envision the improvement of existing techniques which will result with a gain of 10^5 provided by x-ray undulators on a 6 GeV ring. Generally these involve improved resolution in real space, in reciprocal space, in time, and in energy. They involve extensions to studies of lower scattering cross-sections resulting from small sample volume, lower-Z constituents, small displacement modulations, and weak scattering processes. The range of improvement is so vast that lists of specific examples do not do justice to the scientific possibilities.

In spite of the strength of the above arguments, the most exciting science to be done at new facilities will probably not be based on existing methods but on new methods which are simply not possible with current brilliance levels. Two examples of these new techniques are x-ray holography and sub-meV inelastic x-ray scattering. Nevertheless, as strong as this argument is, the history of x-ray and neutron source development shows that even the <u>predicted</u> new techniques are often eclipsed in importance by <u>unpredicted discoveries</u> which occur as scientists begin to actually use the new sources. By providing five orders of magnitude improvement over current facilities, these new sources will undoubtedly be rich sources of scientific discovery.

In preparation of this paper I have benefitted from collaboration and conversation with colleagues too numerous to mention. I hope it will suffice to generally thank the x-ray community for their commitment to synchrotron radiation development.

References

1. "Synchrotron Radiation Research," eds. H. Winick and S. Doniach, Plenum Press, New York (1980).

2. "Handbook on Synchrotron Radiation," Vol. 1, E.-E. Koch, ed., North Holland Publishing Co., Amsterdam (1983).

3. A. Bienenstock and H. Winick, Phys. Today 36, No. 6, 48 (1983).

4. See the Proceedings of the New Rings Workshop (SSRL Report 83/02) Stanford, October 1983, K. Cantwell, ed.

5. See article by E. A. Stearn and S. M. Heald in Ref. 2, p. 955.

6. D. E. Moncton and G. S. Brown, Nucl. Instr. Meth. 208, 579 (1983).

7. B. Buras, Nucl. Instr. Meth. 208, 563 (1983).

8. J. A. Golovchenko, J. R. Patel, D. R. Kaplan, P. L. Cowan, and M. J. Bedzyk, Phys. Rev. Lett. 49, 560 (1982).

9. W. C. Marra, P. Eisenberger, and A. Cho, J. Appl. Phys. 50, 6927 (1979).

10. W. C. Marra, P. H. Fouss, and P. Eisenberger, Phys. Rev. Lett. 49, 1169 (1982).

11. P. Eisenberger and W. C. Marra, Phys. Rev. Lett. 46, 1082 (1981).

12. I. K. Robinson, Phys. Rev. Lett. 50, 1145 (1983).

13. I. K. Robinson, private communication.

14. J. Als-Nielsen and P. S. Pershan, Nucl. Instr. Meth. 208, 545 (1983).

15. D. E. Moncton, R. Pindak, S. C. Davey, and G. S. Brown, Phys. Rev. Lett. 49, 1865 (1982).

16. P. W. Stephens, P. A. Heiney, R. J. Birgeneau, P. M. Horn, D. E. Moncton, and G. S. Brown, Phys. Rev. B29, 3512 (1984); P. A. Heiney, P. W. Stephens, R. J. Birgeneau, P. M. Horn, and D. E. Moncton, Phys. Rev. B28, 6416 (1983).

17. K. L. D'Amico, D. E. Moncton, E. D. Specht, R. J. Birgeneau, S. E. Nagler, and P. M. Horn (to be published).

18. K. Carneiro, W. D. Ellenson, L. Passell, J. P. McTague, and H. Taub, Phys. Rev. Lett. 37, 1695 (1976).

19. D. M. Mills, B. C. Larson, C. W. White, and T. S. Noggle, Nucl. Instr. Meth. 208, 511 (1983).

20. S. Bras, A. Craievich, J. M. Sanchez, C. Williams, and E. D. Zanotto, Nucl. Instr. Meth. 208, 489 (1983).

21. P. M. Platzman and N. Tzoar, Phys. Rev. B2, 3556 (1970).

22. P. Eisenberger and P. M. Platzman, Phys. Rev. B13, 934 (1976).

23. J. B. Hastings, D. E. Moncton, and Y. Fujii, Proceedings of the Workshop on High-Energy Excitations in Condensed Matter, Los Alamos, February 13-15, 1984, R. Silver, ed.

24. S. Doniach, Proceedings of the Workshop on High-Energy Excitations in Condensed Matter, Los Alamos, Feb. 13-15, 1984, R. Silver, ed.

25. See article by R. L. Cohen in Ref. 1, p. 647; A. I. Chechin, N. V. Andronova, M. V. Zelepukhin, A. N. Artem'ev, and E. P. Stepanov, Pis'ma Zh. Eksp. Teor. Fiz. 37, 531 (1983).

Figure Captions

Fig. 1 The history of x-ray sources brilliance is represented by the performance of x-ray tubes including rotating anodes, and various source devices on the SPEAR storage ring. A proposed 6 GeV storage ring designed for synchrotron radiation production could achieve a brilliance of about 10^{19}.

Fig. 2 A summary of the general properties of synchrotron radiation as produced by a uniform magnetic field provided by a storage ring bending magnet and by a periodic field device known as an undulator.

Fig. 3 The properties of the radiation produced by an x-ray undulator on a 6 GeV storage ring would include very high collimation, flux, and brilliance.

Fig. 4 The fundamental physical properties of condensed matter can be categorized according to their spatial and temporal dimensions. Equivalently they are often studied in terms of their energy and wave vector dependence. Current x-ray techniques based on synchrotron radiation cannot routinely access the central region shown above. New synchrotron sources based on undulators on a 6 GeV storage would open this central region to study.

Fig. 5 The principle of a diamond-anvil high pressure cell.

Fig. 6 Schematic illustration (upper figure) of a silicon (111) surface viewed edge-on along a (110) projection. Distances A and B indicate bromine-atom positions above surface. Silicon and bromine atoms are represented by open and closed circles, respectively. The position of the relevant (111) and (220) Fourier components of the charge density are indicated by dashed lines. In the lower figure bromine fluorescence and reflectivity angular yields for (111) Bragg diffraction on a silicon (111) surface. Angular scale is in reduced units where rocking curve width is 2. Ref. 8.

Fig. 7 Grazing incidence scattering geometry.

Fig. 8 Monolayer Pb on Cu(110). Scans (top) show the commensurate (open circles) and incommensurate (filled circles) solid; scans (bottom) as a function of temperature show the changing line shapes as the solid melts. Ref. 10.

Fig. 9 Geometry for diffraction from a horizontal surface is shown in the upper figure. Total reflection ($Q/Q_0 < 0.1$), Fresnel partial reflection and diffraction from smectic A layering at the surface are shown in the lower figure. Ref. 14.

Fig. 10 A scan through the (10) Bragg rod (see reciprocal lattice shown in inset) demonstrates the lack of true long-range order in the two dimensional crystal of $\overline{14}$S5. The scattering fits the power law function (solid line) which is distinctly different from the resolution function (dashed line). Ref. 15.

Fig. 11 A scan through the (10) Bragg rod of a monolayer of Kr adsorbed on a single crystal graphite surface demonstrates the signal rate and resolution obtainable with synchrotron radiation. Ref. 17.

Fig. 12 Results of an initial investigation of laser annealing of pure silicon. Extended Bragg scattering profiles were measured for two different delay times between laser and X-ray bursts; 100 ns (circles) and 195 ns (squares). The "no laser" profile indicates the instrumental resolution. Ref. 19.

Fig. 13 Time evolution of the small angle X-ray scattering at 460°C for a 80 B_2O_3-15 PbO-5 Al_2O_3 glass. The times (min) are 10.0, 18.1, 25.6, 31.1, 37.3, 46.9, 57.0, 67.2, 78.0, respectively, from the bottom to top data sets. Ref. 20.

Fig. 14 An illustration of the energy and momentum transfer regimes accessible using x-ray and neutron probes to study excitations by inelastic scattering. For 14 meV and 100 meV neutron energies, the accessible region is located within the respective inverted parabolas. For a 14.4 keV x-ray, virtually the entire energy-momentum plane is accessible except for a small region $Q(\text{Å}^{-1}) \leq 0.51 \times 10^{-6}$ E (meV). Ref. 23.

Fig. 15 The absolute resolution versus the back-scattering ($2\theta = 179°$) photon energy for the two classes of Bragg reflections in silicon. Ref. 23.

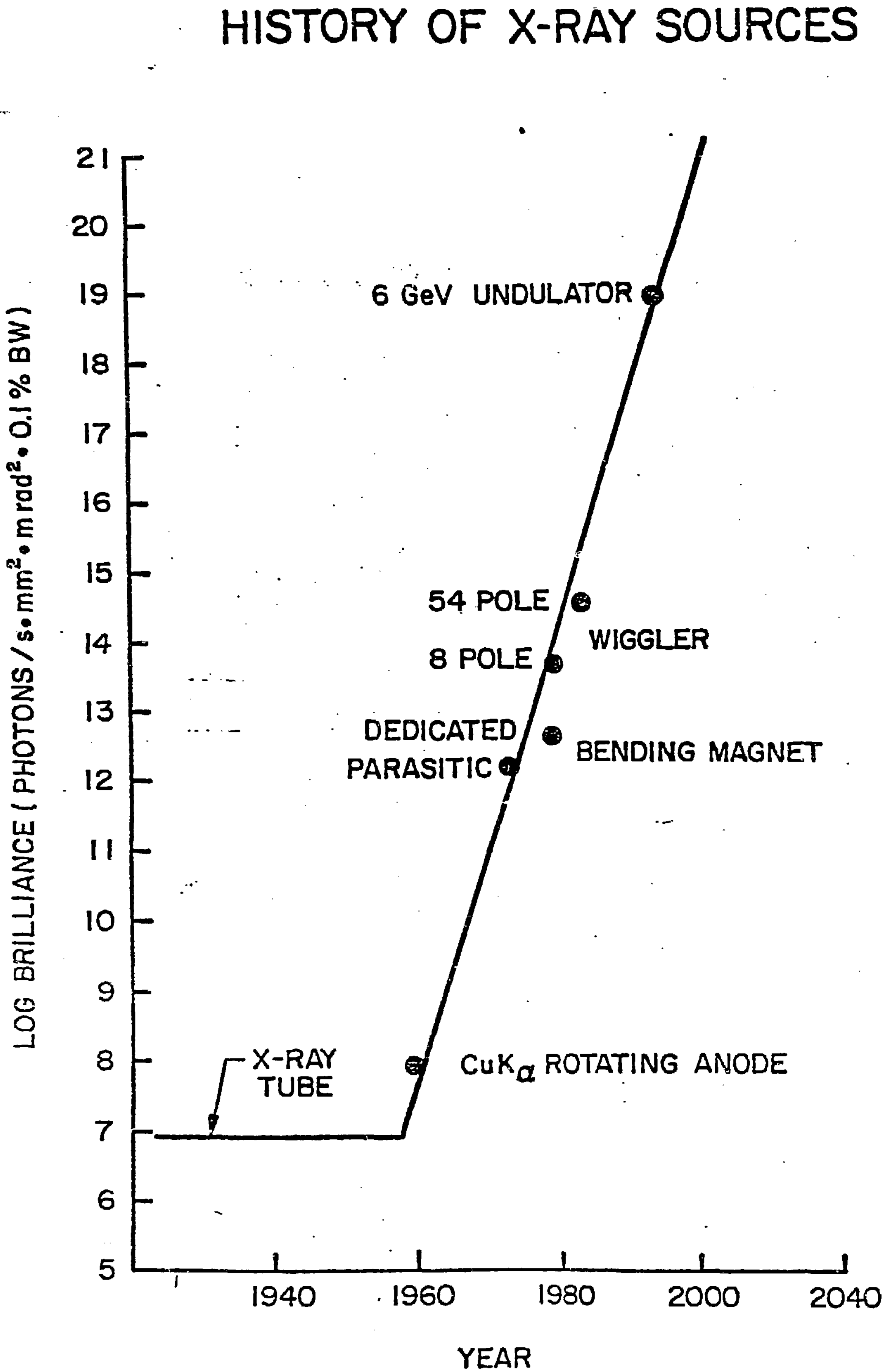
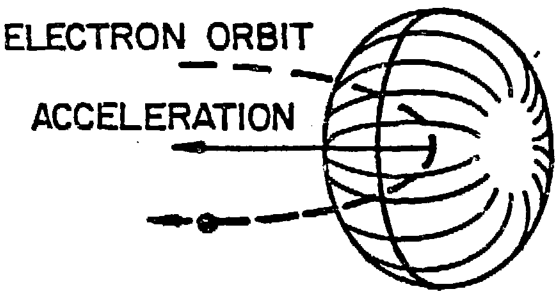
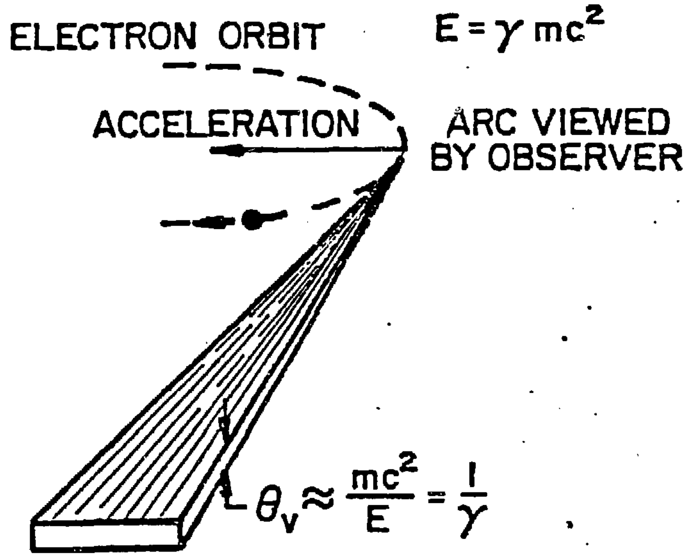

HISTORY OF X-RAY SOURCES
LOG BRILLIANCE (PHOTONS / s • mm² • m rad² • 0.1 % BW)
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
6 GeV UNDULATOR
54 POLE
WIGGLER
8 POLE
DEDICATED
BENDING MAGNET
PARASITIC
X-RAY
TUBE
CuKα ROTATING ANODE
1940
1960
1980
2000
2040
YEAR

Figure 1

SYNCHROTRON RADIATION



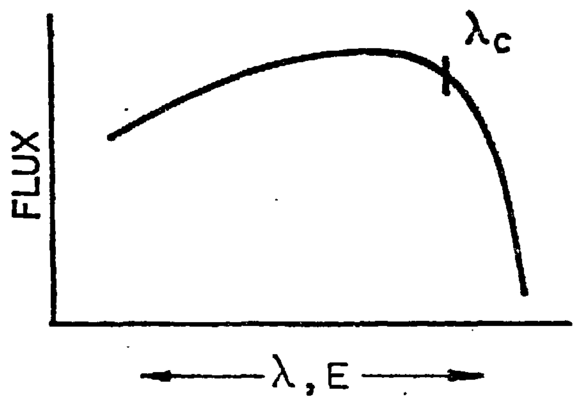


CASE I: $\frac{v}{c} << 1$

CASE II: $\frac{v}{c} \approx 1$

BENDING MAGNET

$$\lambda_c = R/\gamma^3$$



UNDULATOR

$$\lambda_p^m = \frac{\lambda_u}{2m\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = 0.93 \; B(T) \, \lambda_u(cm)$$

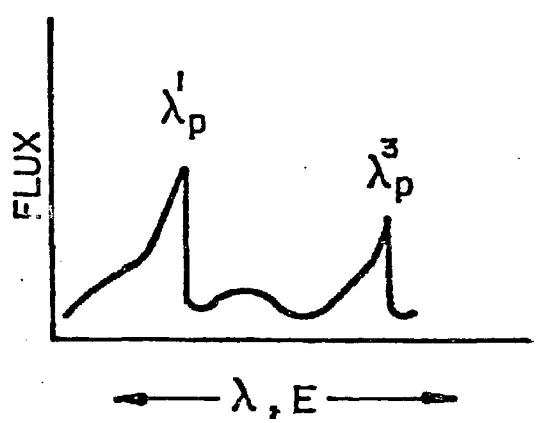


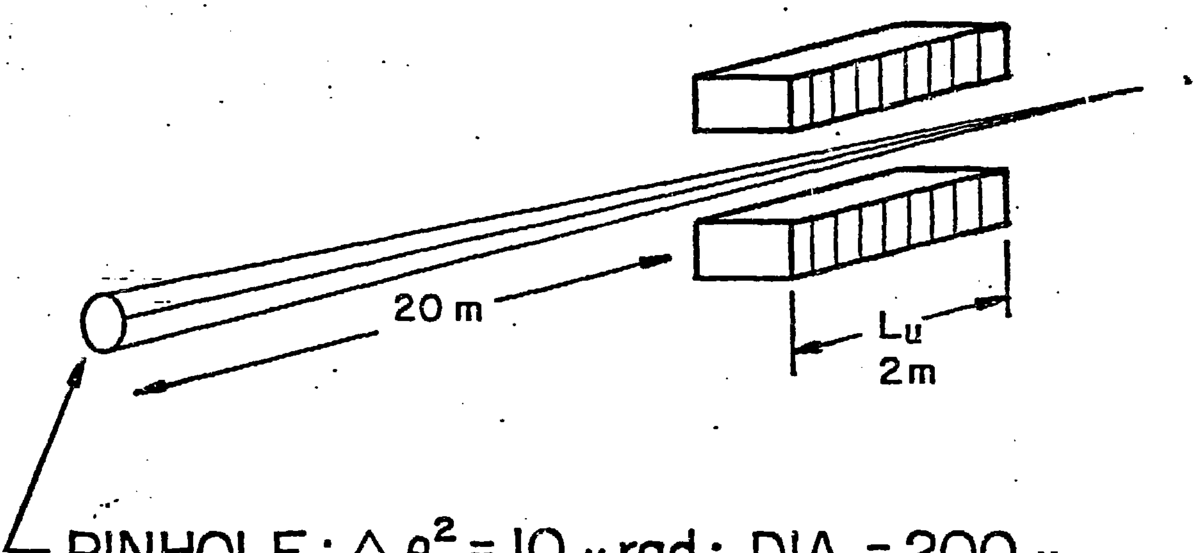
Figure 2

X-RAY UNDULATOR

$E = 6$ GeV $I = 100$ m amp

λ photon $= 1$ Å

$\Delta\theta^2 = 2\lambda_p / L_u$



PINHOLE: $\Delta\theta^2 = 10\,\mu$rad; DIA. = 200 μ

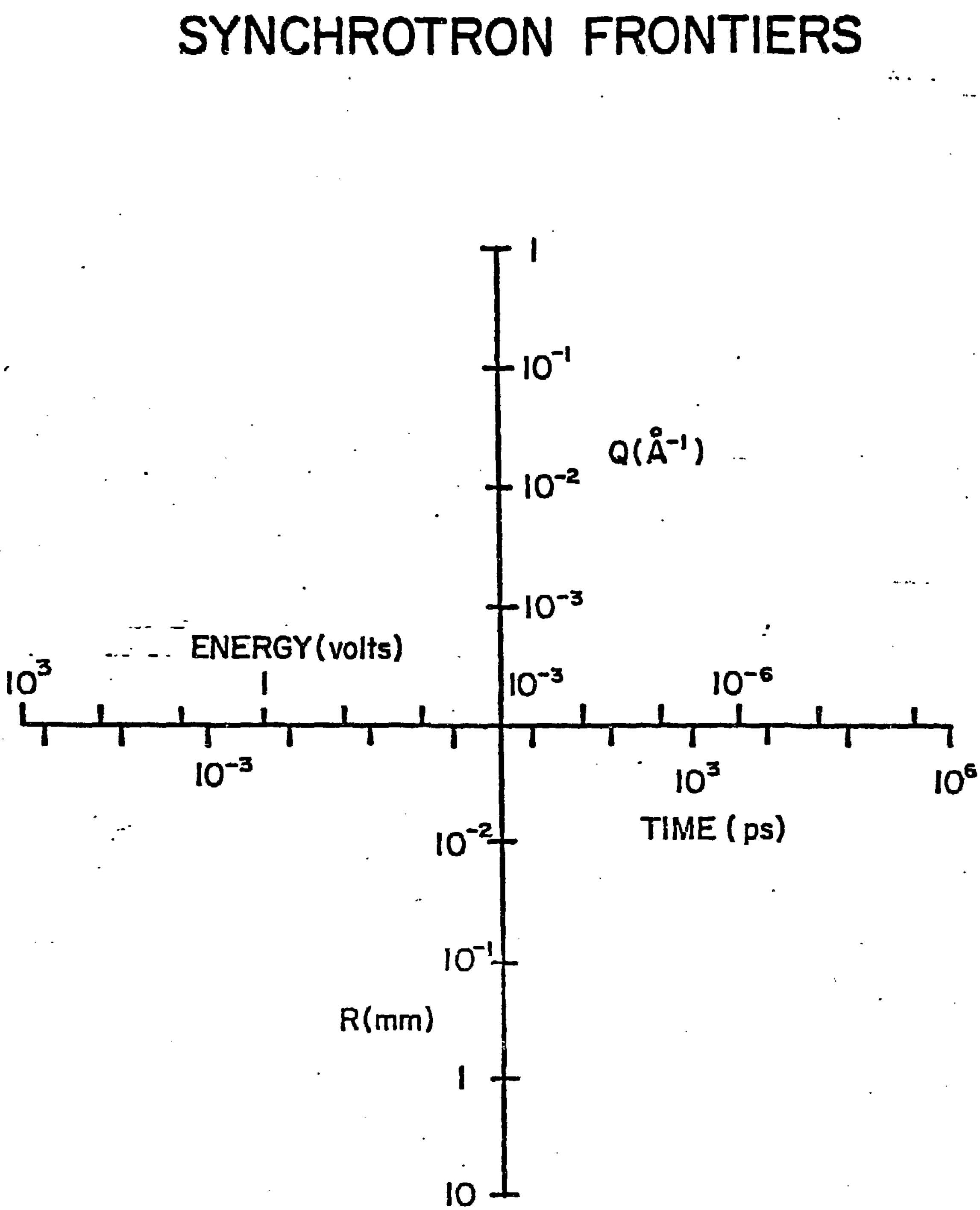
FLUX

~10^{15} photons/s • 0.1% BW • 0.1 amp

BRILLIANCE

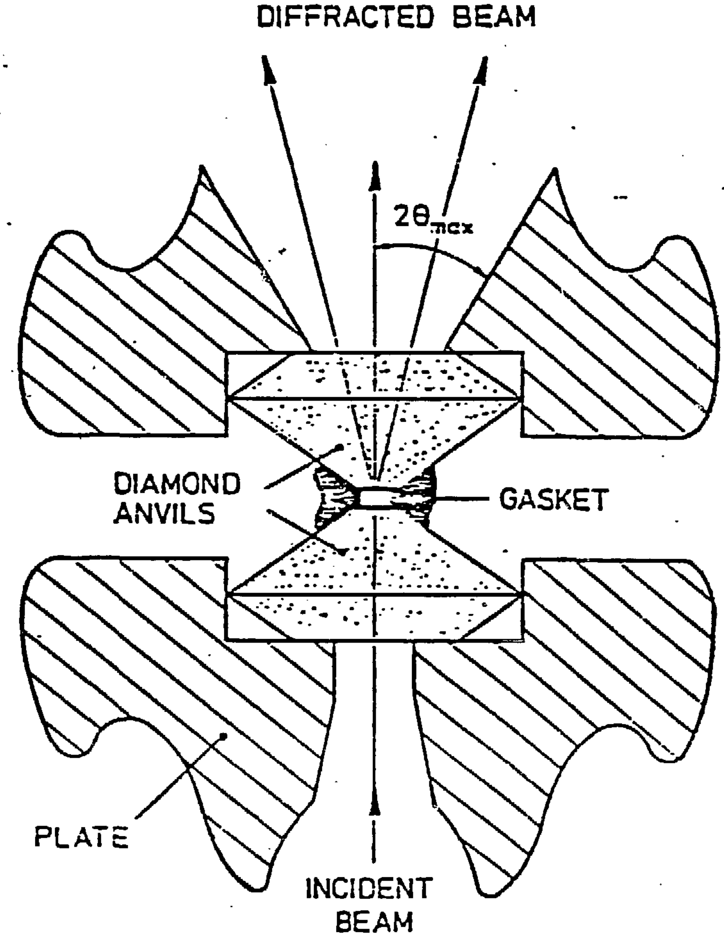
~10^{15} photons/s • mm^2 • m rad^2 • 0.1% BW • 0.1 amp

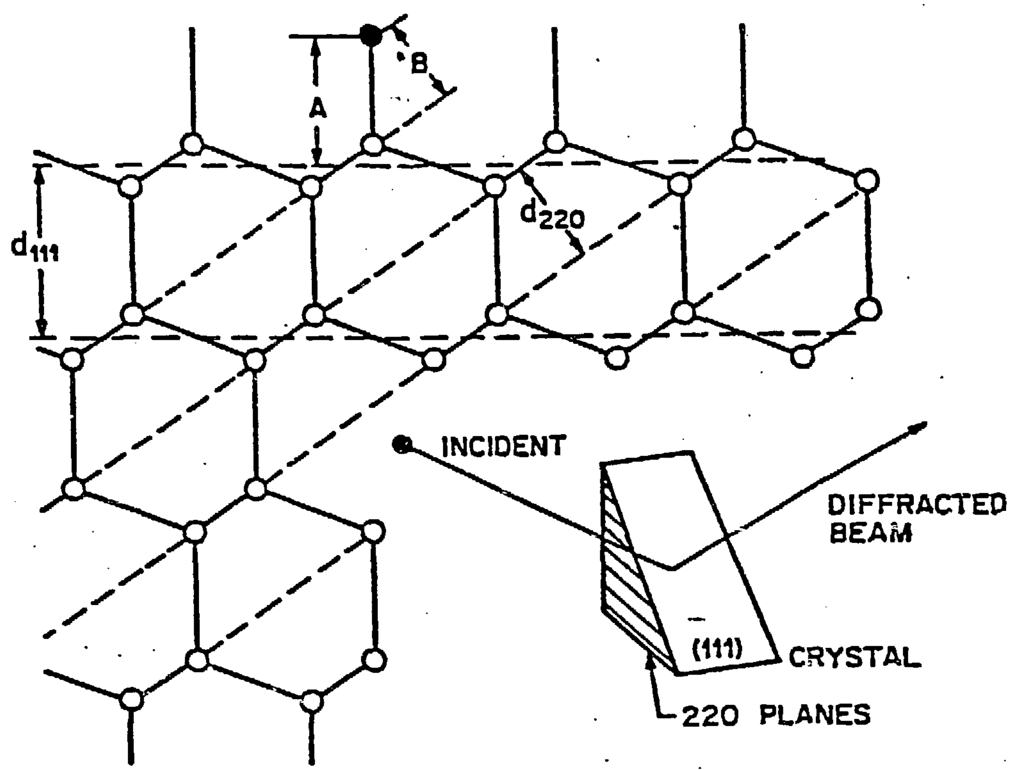
Figure 3



SYNCHROTRON FRONTIERS
1
10^{-1}
Q(Å^{-1})
10^{-2}
10^{-3}
ENERGY (volts)
10^{3}
1
10^{-3}
10^{-6}
10^{-3}
10^{3}
10^{6}
TIME (ps)
10^{-2}
10^{-1}
R(mm)
1
10

Figure 4


DIFFRACTED BEAM
2θmax
DIAMOND ANVILS
GASKET
PLATE
INCIDENT BEAM


B
A
d_{111}
d_{220}
INCIDENT
DIFFRACTED BEAM
(111)
CRYSTAL
220 PLANES

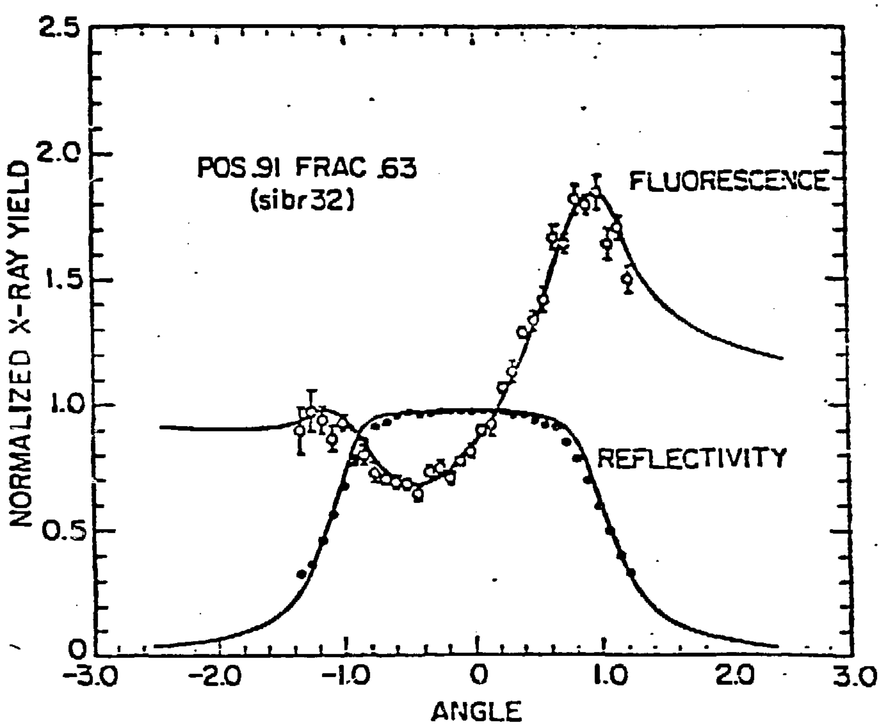

POS .91 FRAC .63
(sibr32)
FLUORESCENCE
REFLECTIVITY
NORMALIZED X-RAY YIELD
ANGLE
2.5
2.0
1.5
1.0
0.5
0
-3.0
-2.0
-1.0
0
1.0
2.0
3.0

Figure 6

GRAZING INCIDENCE SCATTERING

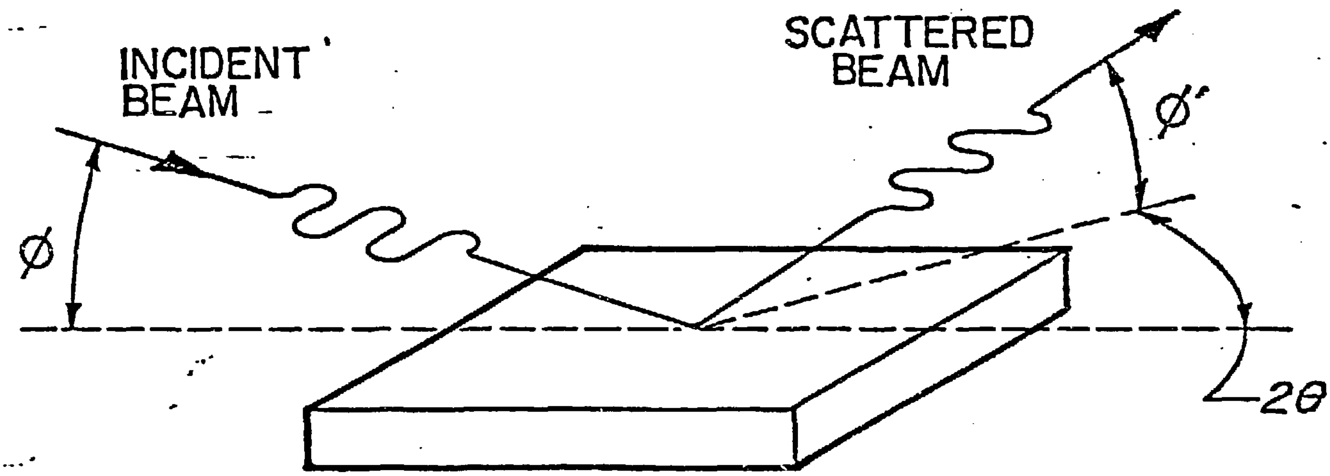
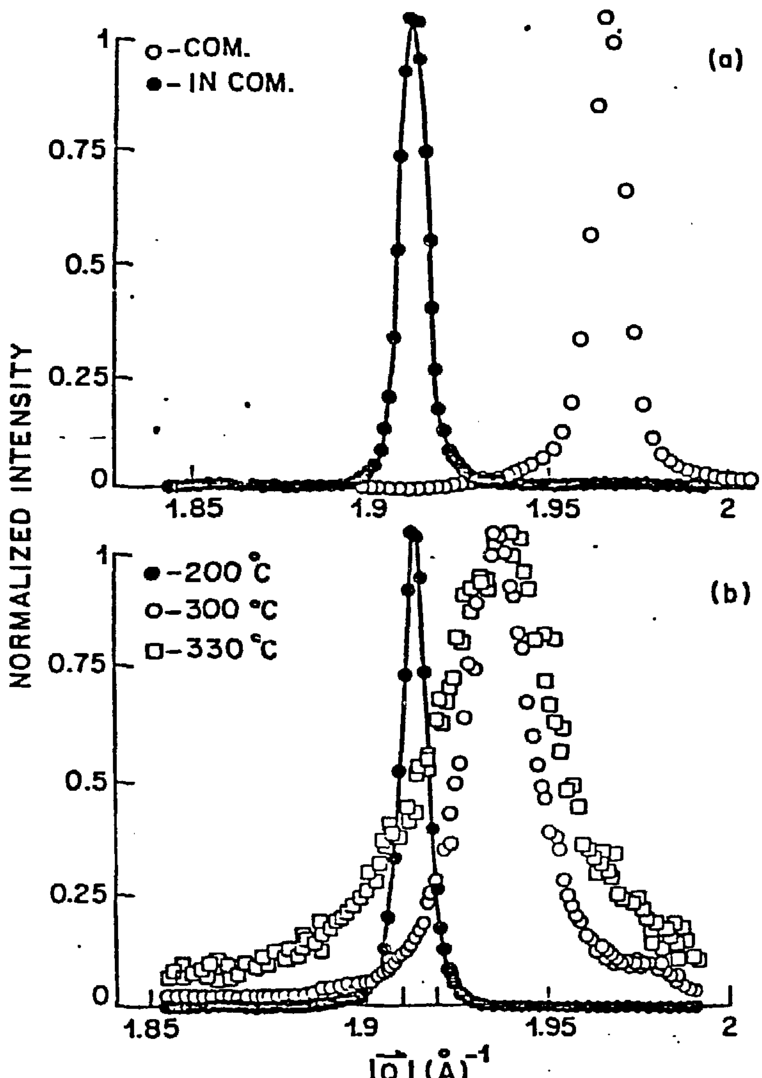
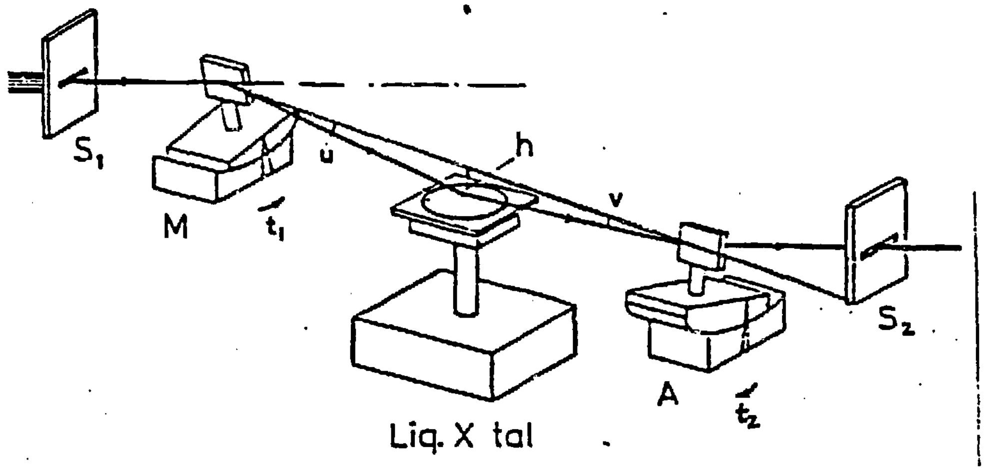


Figure 7



o-COM.
●-IN COM.
(a)
●-200 °C
o-300 °C
□-330 °C
(b)
NORMALIZED INTENSITY
1
0.75
0.5
0.25
0
1.85
1.9
1.95
2
|Q| (Å)^-1

Figure 8


S1
M
t1
u
h
v
Liq. X tal
A
t2
S2

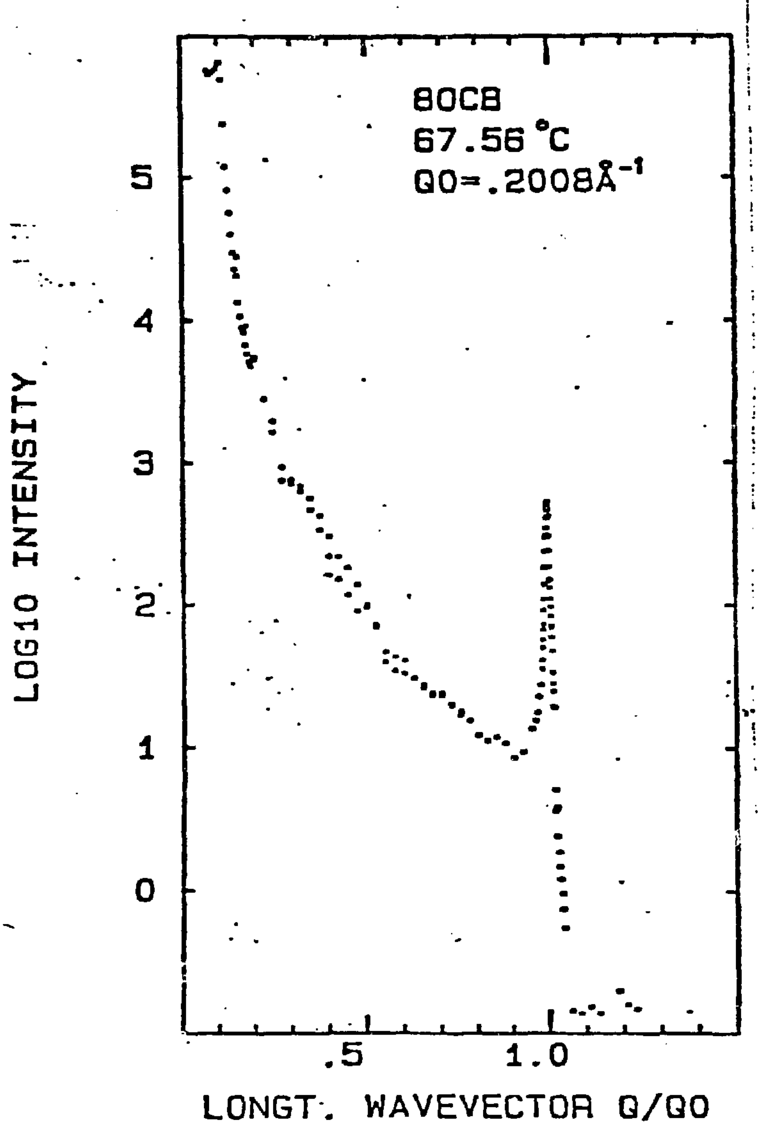
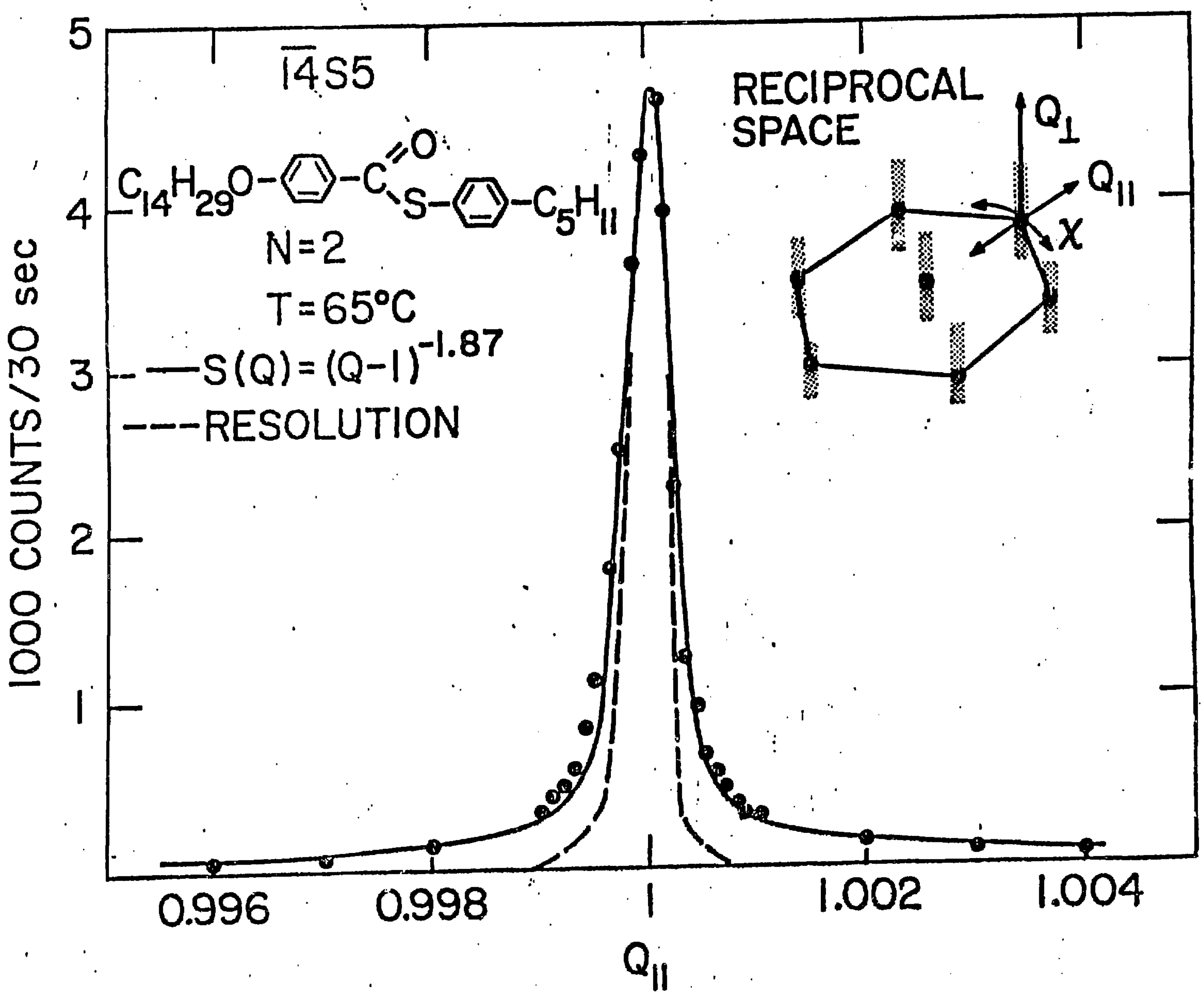

8OCB
67.56 °C
Q0=.2008Å⁻¹
LOG10 INTENSITY
LONGT. WAVEVECTOR Q/Q0
5
4
3
2
1
0
.5
1.0

Figure 9



1000 COUNTS/30 sec
5
4
3
2
1
$\overline{14}$S5
$C_{14}H_{29}O-\bigcirc-C(=O)-S-\bigcirc-C_5H_{11}$
N=2
T=65°C
—S(Q)=(Q−1)^{−1.87}
---RESOLUTION
RECIPROCAL SPACE
Q⊥
Q∥
χ
0.996
0.998
1
1.002
1.004
Q∥

Figure 10

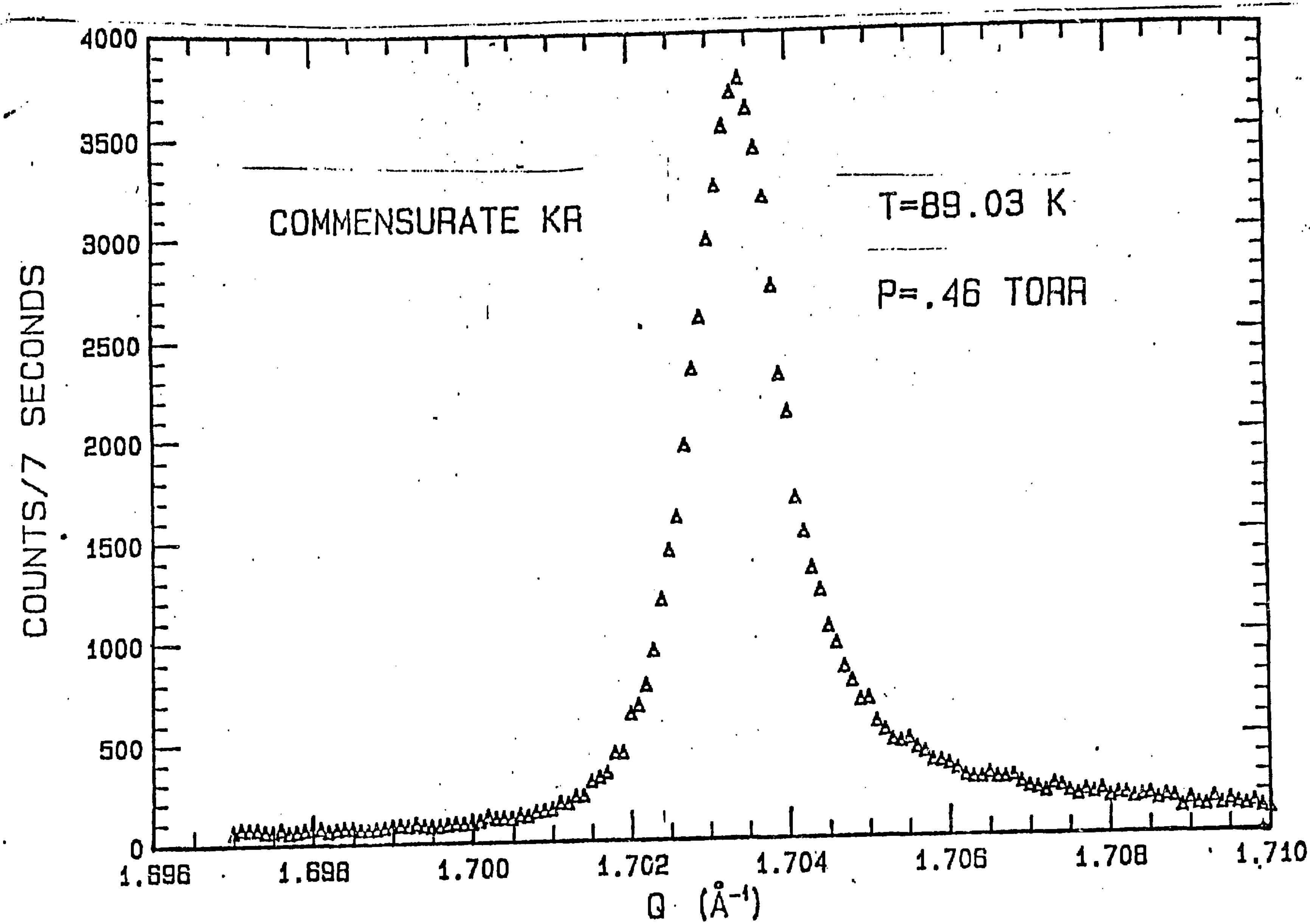

COMMENSURATE KR
T=89.03 K
P=.46 TORR
COUNTS/7 SECONDS
4000
3500
3000
2500
2000
1500
1000
500
0
1.696
1.698
1.700
1.702
1.704
1.706
1.708
1.710
Q (Å⁻¹)

Figure 11

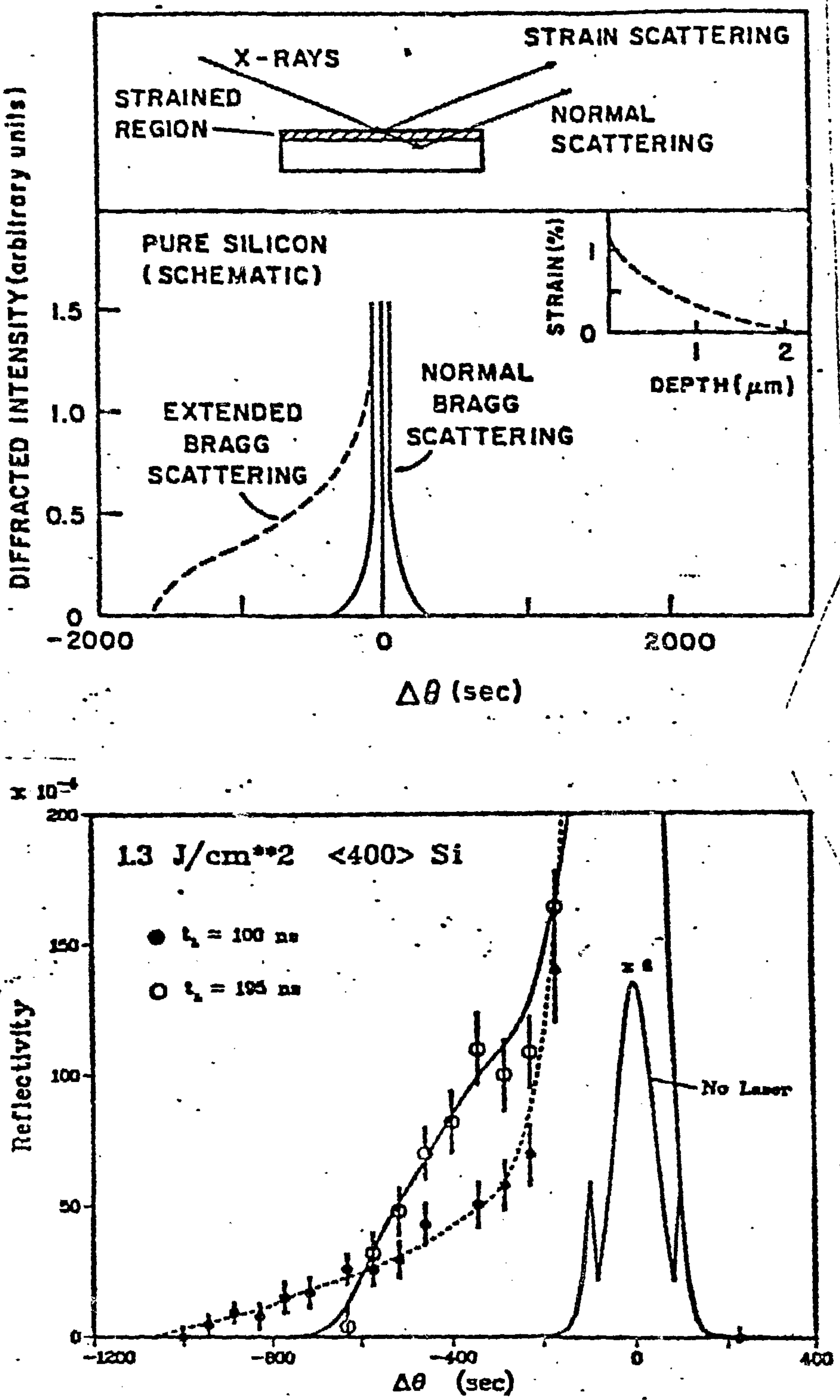

X-RAYS
STRAIN SCATTERING
STRAINED REGION
NORMAL SCATTERING
DIFFRACTED INTENSITY (arbitrary units)
PURE SILICON (SCHEMATIC)
STRAIN (%)
DEPTH (μm)
NORMAL BRAGG SCATTERING
EXTENDED BRAGG SCATTERING
1.5
1.0
0.5
0
−2000
0
2000
Δθ (sec)
x 10^-4
1.3 J/cm**2 <400> Si
Reflectivity
No Laser
200
150
100
50
0
−1200
−800
−400
0
400
Δθ (sec)

Figure 12

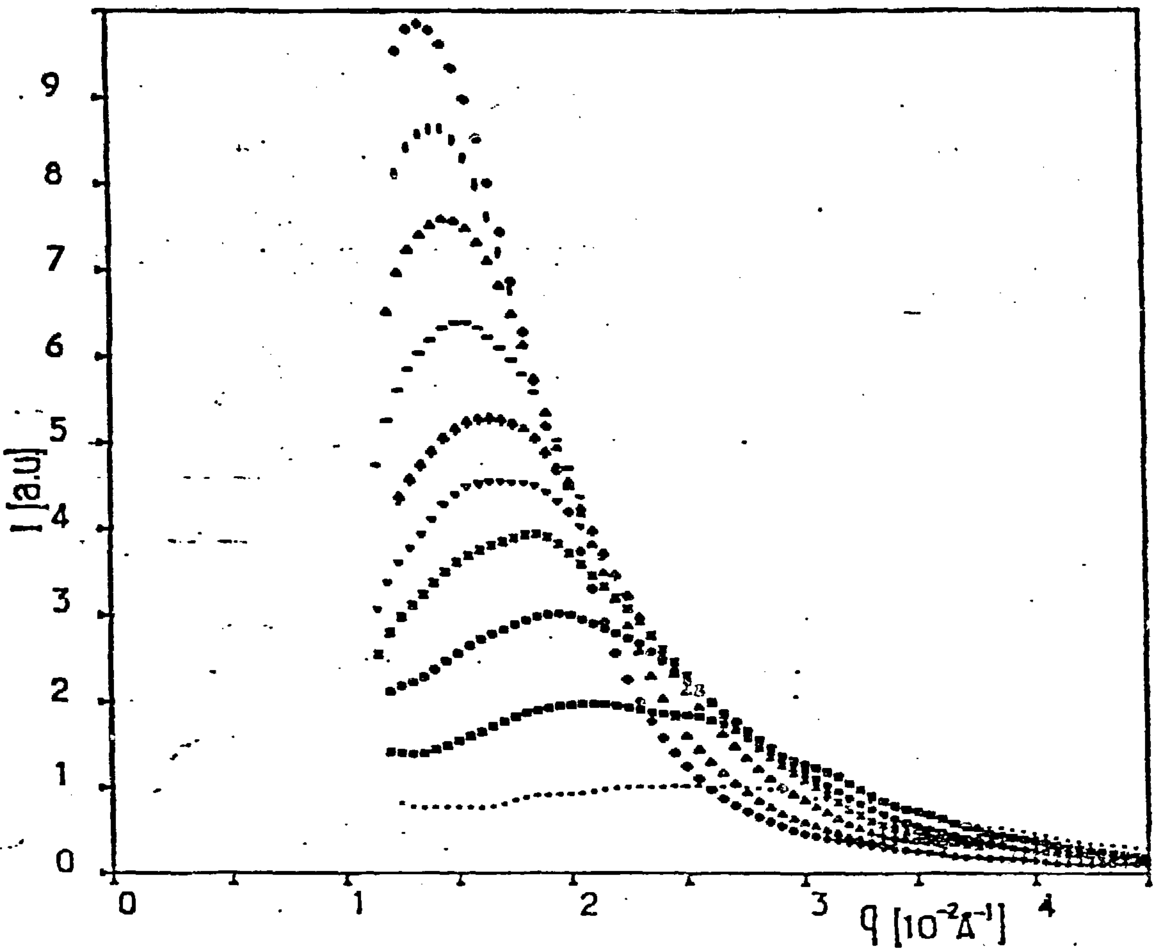
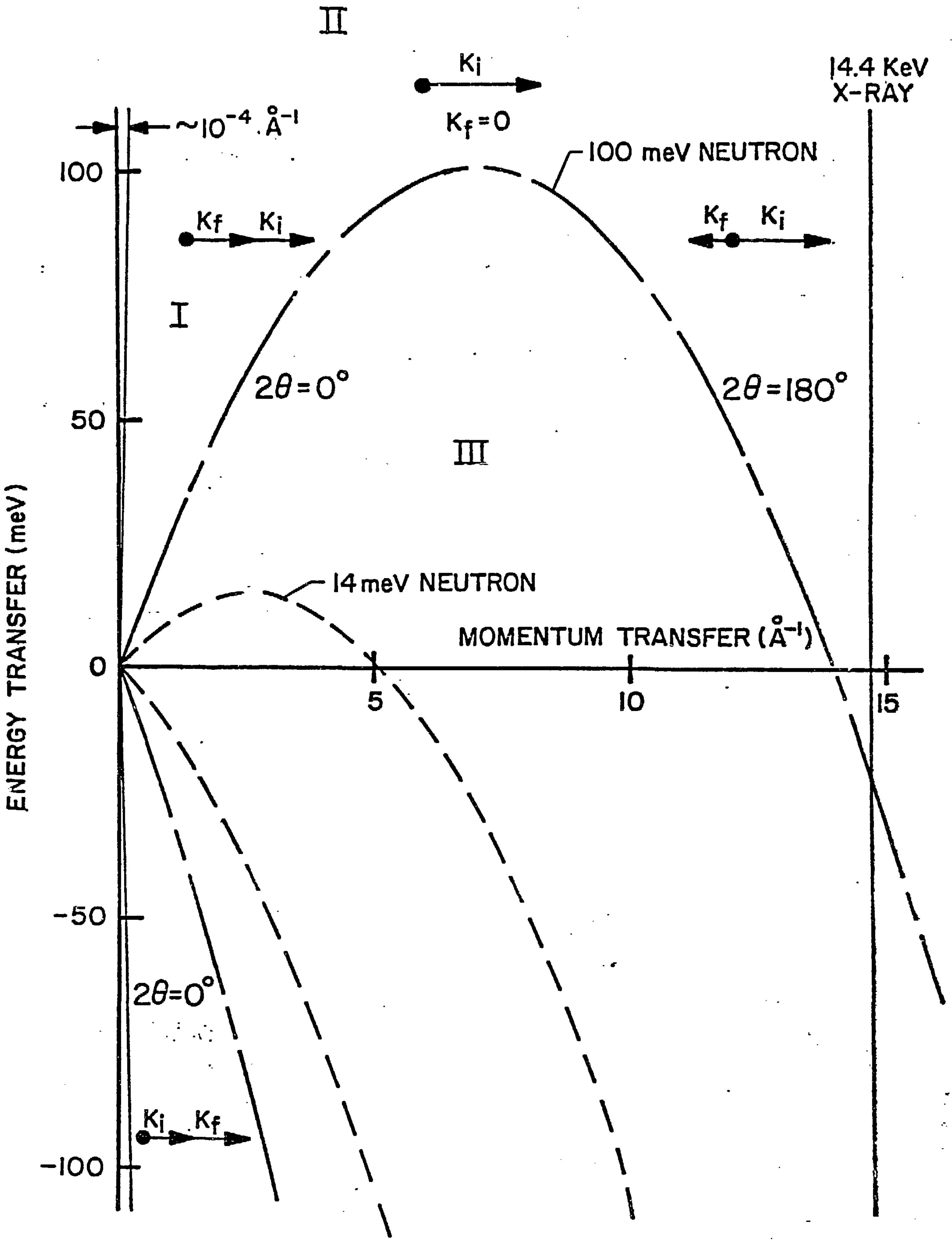
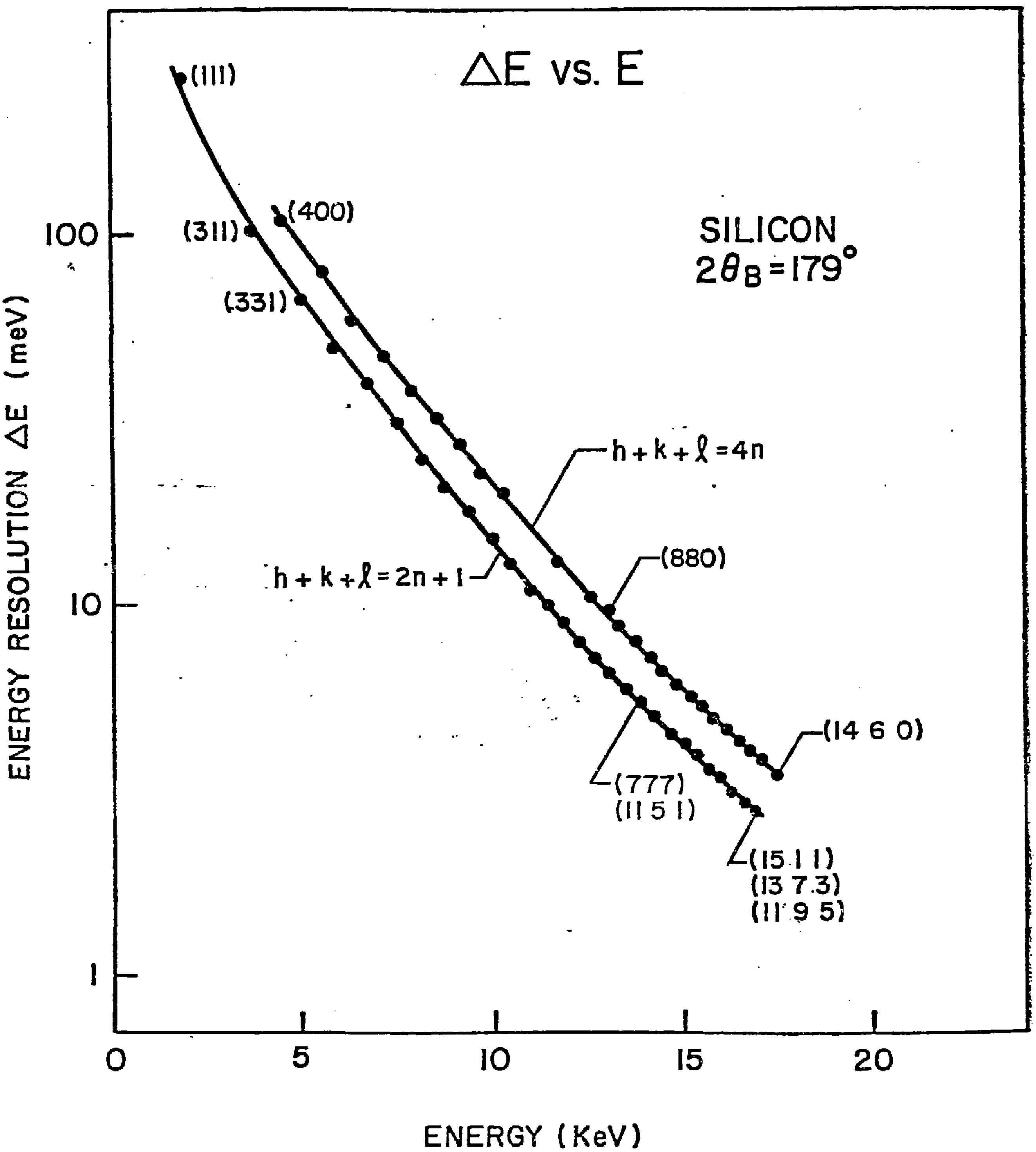


Figure 13



II
K_i
$K_f=0$
14.4 KeV X-RAY
~10^{-4} Å^{-1}
100 meV NEUTRON
100
K_f K_i
K_f K_i
I
2θ=0°
2θ=180°
50
III
ENERGY TRANSFER (meV)
14 meV NEUTRON
MOMENTUM TRANSFER (Å^{-1})
0
5
10
15
−50
2θ=0°
K_i K_f
−100

Figure 14



ΔE vs. E
SILICON
2θB = 179°
(111)
(311)
(400)
(331)
h + k + ℓ = 4n
h + k + ℓ = 2n + 1
(880)
(14 6 0)
(777)
(11 5 1)
(15 1 1)
(13 7 3)
(11 9 5)
100
10
1
0
5
10
15
20
ENERGY RESOLUTION ΔE (meV)
ENERGY (KeV)

Figure 15